Height of Crown Scorch in Forest Fires

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A relation between fire behavior and crown scorch height is derived from measurements on 13 experimental outdoor fires. The range of data includes fire intensities from 16 to 300 kcal/s-m, and scorch heights from 2 to 17 m. The results agree with established theory that scorch height varies with the 2/3 power of line-fire intensity. The effects of air temperature and wind speed on scorch height are treated as well. The derived relations could be useful to those interested in prescribed burning under a crown canopy, ecological response of trees to fires of varying intensity, and timber losses following forest fires.

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L'auteur dérive un rapport entre le comportement du feu et la hauteur de roussissement de la cime lors de 13 incendies de forêts expérimentaux. L'éventail des données inclut des intensités du feu de 16 à 300 kcal/s-m et des hauteurs de roussissement de 2 à 17 m. La théorie est confirmée par les expériences: la hauteur de roussissement varie selon la puissance 2/3 de l'intensité de la ligne de feu. L'auteur étudie aussi l'effet de la température ambiante et de la vitesse du vent sur la hauteur de roussissement. Ces rapports pourront intéresser ceux qui étudient les brûlages dirigés sous une voûte foliacée, la réaction écologique des arbres aux incendies d'intensités diverses et les pertes de bois d'œuvre à la suite d'incendies de forêts.

Introduction

The crucial question about the effect of any forest fire is: will the trees live or die? The answer is obvious for crown fires and high intensity fires in general; trees of all sizes are of course killed outright. Fires of low or variable intensity, however, may leave a stand damaged or only partly killed. The quantitative link between the behavior of the fire and the amount of mortality then becomes of practical interest to the ecologist studying the responses of the forest to fire of varying intensity, to the economist assessing fire losses, and especially to the forester using prescribed fire under a full or partial forest canopy. There are several possible uses for prescribed fire in such a situation: disposal of slash from partial cutting; control of shrub vegetation; or preparation of seedbeds for regeneration. Whatever the aim, the prime limitation is that excessive damage to the standing trees be avoided.

Above any forest fire burning on the surface of the ground there is a zone within which foliage will be scorched and killed by hot gases rising from the flames. It is fairly well established, for pine species at least, that the principal cause of mortality following fire is crown scorch rather than damage to the cambium near the ground (*e.g.* Cooper and Altobellis 1969; Van Wagner 1970). Cambial damage to the lower trunks of large trees is by comparison, a minor consideration. Any resultant fire scars lower the tree's economic value, but do not directly affect the health and growth rate. To die by cambial damage alone, a tree must be completely girdled, and any fire intense enough to girdle a large tree is usually intense enough to scorch all its foliage as well. Death follows quickly from complete crown scorch but may take several years following girdling. Some tree species can stand the loss of considerable crown foliage without dying, although growth rate may be affected for a while. Methven (1971) found that mature red and white pines have a 50% chance of surviving the loss of three-quarters of their foliage.

In this paper, some data relating lethal scorch height to fire behavior are presented along with some theory that partially accounts for the result.

Theory

The temperature reached at any height in the convection column above a fire depends on three things: the intensity of the heat source, the ambient temperature, and the wind speed. At a given fire intensity, higher winds tend to level the convection column, reducing the lethal height. The ambient temperature enters the picture because the increase in temperature needed to kill the foliage is naturally dependent on the starting point.

A well established relation (*c.f.* Thomas 1963) links the intensity, I, of a line fire and the height, h, at which a given temperature, ΔT, above ambient is reached in the convection above the fire. It is based on dimensional analysis of the pertinent variables, and, at appreciable height above the flame, is independent of the thickness of the flaming front:

[1] $h \propto I^{2/3}/\Delta T$

This simple relation applies, however, in still air only, and the introduction of wind causes severe complication. The following treatment is adapted from the work of Taylor (1961), developed further by Thomas (1964).

Above the flame, the plume in still air has the form of a wedge whose thickness increases with height as air is entrained from both sides. As plume volume increases, temperature decreases. Vertical velocity, however, theoretically remains constant as long as the wedge is intact.

There are two possible extremes of the effect of wind on a rising heat plume. In very light wind, it is reasonable to assume that the plume is simply tilted without being seriously distorted. In very strong wind, on the other hand, the rising gas is quickly mixed with the horizontal airstream. The upwind face of the plume may still be definable, but the downward face does not exist unless taken to be the ground surface itself. In the light-wind case, the limiting condition is reached when the wind speed equals the horizontal velocity at which air is entrained into the plume. Since, according to Thomas (1963), the entrainment velocity is only about 16% of the plume velocity, and plume velocities in low intensity fires are of the same order as moderate wind speeds, the true light-wind case is strictly possible only at very low wind speeds, say no more than 1 m/s. A great range of situations no doubt exists between these two extreme cases.

Both Taylor (1961) and Thomas (1964) were mainly concerned with the strong-wind case, whereas for fires burning under a forest canopy the light-wind case is probably more applicable. However, both Taylor and Thomas do derive a relation between wind, U, and the angle, A, that the plume makes with the ground in light winds:

[2] $\tan A \propto (bI/U^3)^{1/2}$

where

[3] $b = g/dcT_0$

Here g is the acceleration due to gravity, d is air density, c is specific heat of air, and T_0 is the ambient absolute temperature. This group of variables must be included for dimensional reasons, but can be considered constant for practical purposes. Using Thomas' values for g, d, and c, and 298 °K for T_0, the numerical value of b in the unit system m-s-kg-kcal-°K works out to 0.107. Its dimensions are such that the product bI has the same dimensions as the cube of velocity. Note that, since b varies with absolute temperature, the effect of a few degrees is very slight. Keeping b constant is therefore justified, and the variable ΔT is adequate to account for the effect of air temperature on h.

When the plume travels a tilted path, the vertical height is presumably dependent on $\sin A$, so that:

[4] $h \propto \dfrac{I^{2/3} \sin A}{\Delta T}$

The sine of A is readily found from Eq. [2] for $\tan A$:

[5] $\sin A \propto [bI/(bI + U^3)]^{1/2}$

Substituting (5) in (4) yields:

[6] $h \propto \dfrac{b^{1/2} I^{7/6}}{\Delta T (bI + U^3)^{1/2}}$

The lethal temperature for live crown foliage is about 60 °C according to Kayll (1968) and Methven (1971). The term $(60 - T)$, where T is air temperature in degrees centigrade, can therefore be inserted in place of ΔT. The need for considering the variable group b is now apparent if the bracketed sum in the denominator is to make sense. The factor $b^{1/2}$ in the numerator, however, can be blended into a final proportionality coefficient, k. Then, inserting the value of b in the denominator, the expression for scorch height h_s in terms of fire intensity, I, air temperature, T, and wind, U, becomes:

[7] $h_s = k\, I^{7/6}/(60 - T)(0.107\, I + U^3)^{1/2}$

The unit system is m-s-kcal-°C. Evidently, this general Eq. [7] rests on a weak theoretical basis compared with the simple one for the still-air case [1]. In particular, it cannot be expected to hold well as the wind becomes strong enough to badly distort the convection plume.

Results

Information on fire intensity and crown scorch height was available for 13 experimental fires. Eight were in a red and white pine stand, two in jack pine, one in red oak, and two in a red pine plantation. Plot size varied from 0.07 to 0.10 ha. Line-fire intensity as rate of energy output per unit length of front was calculated from measurements of rate of spread and of fuel weight before and after burning. A common value for low heat of combustion (4500 cal/g) was used for all fires. Fire intensity is then the product of rate of advance, fuel weight consumed per unit area, and heat of combustion, all in compatible units. Strictly speaking, only convectional heat should be considered for present purposes, and a deduction made for radiant heat, which at low fire intensity has a negligible effect on crown damage in the overstory. However, there is no sound available basis for estimating radiant heat as a proportion of the total energy output of individual fires of different intensities, so the gross energy output was used for convenience.

Height of scorch was measured at all available points within each plot, allowing reasonable surrounds for reduced intensity near the edges. The number of points varied from three to ten. Only points showing a clear distinction between dead foliage below and live foliage above were counted. The range of data includes fire intensities from 16 to 300 kcal/s-m, and average scorch heights from 2 to 17 m.

The first test of the data was to plot scorch height h_s separately over two forms of fire intensity, I, the plain value and the 2/3 power. It was obvious at once that the scorch heights fell along a better straight line when plotted over $I^{2/3}$ than over I. The graph based on $I^{2/3}$ also resulted in a y-intercept much closer to the theoretically correct zero (0.48 m for $I^{2/3}$, 2.99 m for I). It was concluded that $I^{2/3}$ was the proper independent variable, as predicted by Eq. [1].

In the second test of the data, the scorch heights h_s were graphed in the following three ways: against the 2/3 power of fire intensity, against intensity and air temperature as in Eq. [4], and finally against intensity, temperature, and wind as in Eq. [7]. Straight lines were fitted to all three cases, arranged to pass through the origin. The resultant equations for h_s were:

[8] $h_s = 0.385I^{2/3}$

[9] $h_s = 11.61I^{2/3}/(60 - T)$

[10] $h_s = \dfrac{3.94I^{7/6}}{(0.107I + U^3)^{1/2}(60 - T)}$

The relation between h_s and I appears in Fig. 1, and correlation of h_s with the 2/3 power of I is, as the theory predicts, very good. Equations [8], [9], and [10] all have $r^2 = 0.98$, a degree of fit which, in view of the rough nature of the data, is probably somewhat fortuitous.

Two additional graphs are presented to show the possible effects of varying air temperature and wind predicted by these equations. Theoretical variation of scorch height with air temperature in still air (Eq. [9]) is shown in Fig. 2, and with wind at a constant 25 °C (Eq. [10]) in Fig. 3. Each figure contains curves for three levels of constant intensity.

Discussion

Since scorch height for the present set of fires is so well correlated with fire intensity alone, there is not much room for improvement by adding the effects of air temperature and wind. However, even if the fit of h_s with $I^{2/3}$ had been poorer, it is possible that consideration of T and U would still not have improved the picture very much. The reason is seen in Figs. 2 and 3, which show that the ranges of T and U in the present data are too small to effectively test the theory of their effects on scorch height.

The curves in Figs. 2 and 3 represent theoretical variation in scorch height at constant intensity. Note that as one factor affecting intensity varies, another must vary also, in a compensating direction, if intensity is to be held constant. Thus, since wind speed markedly affects fire intensity, the curves in Fig. 3 must
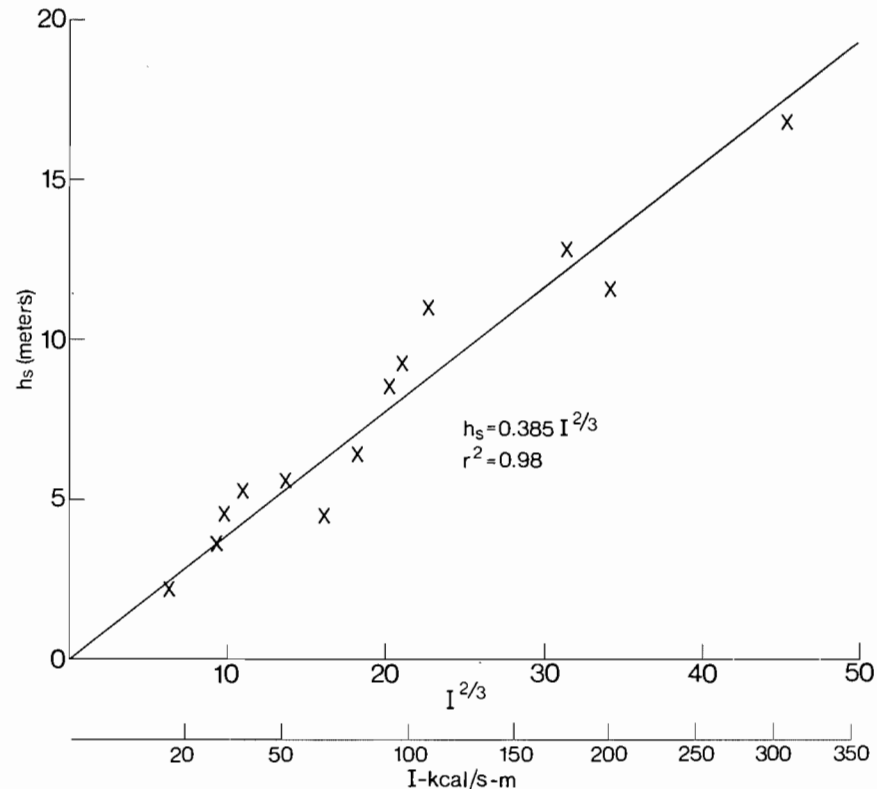
FIG. 1. Experimental relation between scorch height, h_s, and fire intensity, I. Scale of x-axis is $I^{2/3}$; nonlinear scale of I shown as well.

each represent a series of fires burning at increasing wind speed and increasing fuel moisture. In other words, if wind speed should vary during a single fire, the scorch height could not be expected to follow a curve like those in Fig. 3. Rather, as wind increased, the increase in fire intensity would more than offset the flattening effect of wind, and the scorch height would rise.

There is another variable, namely foliar moisture content, that might affect scorch height. The old foliage of conifers undergoes a pronounced dip in foliar moisture content before the new growth flushes in late spring (Van Wagner 1967). Also, the new foliage flushes in a very succulent state, and remains moister than the old foliage until late summer. It is, however, the specific heat of the live foliage on a wet basis rather than the moisture content on the usual dry basis that is pertinent in this question. Since the calculated specific heat of

live foliage only increases some 15% from the lower to the upper limit of moisture content normally found in conifer foliage, it is unlikely that the lethal scorch heights for old and freshly-flushed foliage would ever differ by more than a few feet.

A single lethal foliage temperature of 60 °C was chosen for the present analysis. Actually, as is well known, time and temperature work together. Conifer foliage stands 60 °C for about a minute according to Kayll (1968) and others quoted by Hare (1961); for death at 50 °C at least 10 min is required. The practical lethal temperature range is thus only about 10 centigrade degrees, and variation within this limited range would not affect the present analysis appreciably.

Simple desiccation below 60 °C is not likely to cause appreciable damage, since conifer foliage loses moisture very slowly at such temperatures. For example, white pine foliage held
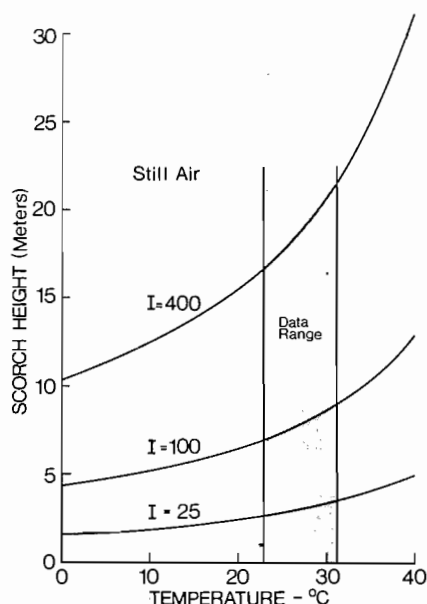
FIG. 2. Theoretical relation between scorch height h_s and air temperature, T, in still air for three intensity levels; curves calculated from Eq. [9]. Actual data range shown.
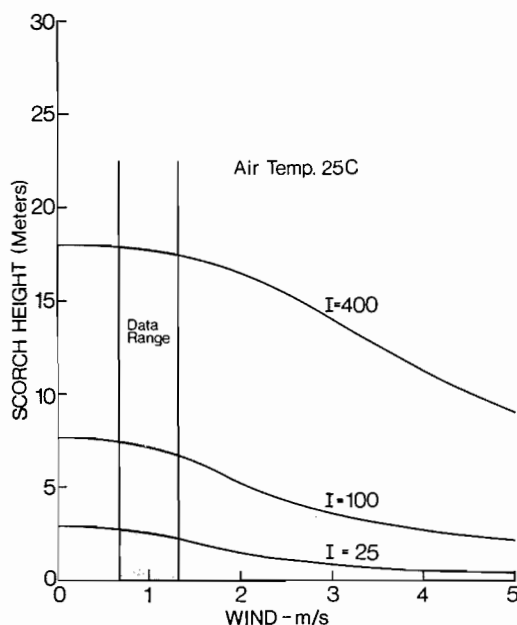

FIG. 3. Theoretical relation between scorch height, h_s, and Wind, U, at 25 °C for three intensity levels; curves calculated from Eq. 10. Actual data range shown.

at 60 °C in the drying oven for 16 min loses only 10 points out of an initial 130% moisture content, dry basis. The main convective heat pulse from a forest fire lasts only a few minutes.

The proportion of foliage scorched is, of course, only one factor among several that determine whether a conifer tree will live or die. Dormant buds, if present, are more difficult to kill because of their bulk alone. In addition, lethal temperatures are said to be higher in all tissues during the dormant season. These factors are dealt with by Methven (1971), Kayll (1968), Byram (1958), and others.

Conclusion

The main conclusion to be drawn from the present work is that the lethal scorch height varies with the 2/3 power of line-fire intensity. This simple relation should provide a satisfactory guide to the kind of prescribed fire permissible under a stand whose crown height is known, or to the likely degree of damage following wildfire. If air temperature or wind differ markedly from average, then their additional effects may be tentatively estimated from the theory presented.

It is apparent from Fig. 1 that only fires of relatively low intensity are fairly sure to cause no crown damage. Intensities less than 100 kcal/s-m (scorch height 8 m) should kill little or no tree foliage; above 200 kcal/s-m (scorch height 13 m) many stands would suffer damage. These data, of course, represent average values over an area, and variation within a single fire may be considerable. Although extrapolation of such empirical data is always doubtful, it looks as though an intensity of 1000 kcal/s-m (scorch height about 40 m) represents a level of fire intensity that very little of the Canadian forest could survive.

BYRAM, G. M. 1958. Some basic thermal processes controlling the effects of fire on living vegetation. U.S. For. Serv., Southeast. For. Exp. Stn. Res. Note 114.

COOPER, R. W., and ALTOBELLIS, A. T. 1969. Fire kill in young loblolly pine. Fire Control Notes, 30(4), 14–15.

HARE, R. C. 1961. Heat effects on living plants. U.S. For. Serv., South. For. Exp. Stn. Occas. Pap. 183.

KAYLL, A. J. 1968. Heat tolerance of tree seedlings. Proc. Eighth Annu. Tall Timbers Fire Ecol. Conf., Tall Timbers Res. Stn., Tallahassee, Fla. pp. 89–105.

METHVEN, I. R. 1971. Prescribed fire, crown scorch, and mortality: field and laboratory studies on red and white

pine. Can. For. Serv., Petawawa For. Exp. Stn. Inf. Rep. PS-X-31.

TAYLOR, G. I. 1961. Fire under the influence of natural convection. *In* The use of models in fire research. Nat. Acad. Sci., Nat. Res. Counc. Can., Publ. 786, pp. 10–31.

THOMAS, P. H. 1963. The size of flames from natural fires. Proc. Ninth Int. Symp. Combust. Academic Press, New York, N.Y. pp. 844–859.

——— 1964. The effect of wind on plumes from a line heat source. Joint Fire Res. Organ., Fire Res. Stn., Boreham Wood, Engl. Fire Res. Note 572.

VAN WAGNER, C. E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires. Can. Dep. For. Rural Develop. Dep. Publ. 1204.

——— 1970. Fire and red pine. Proc. Tenth Annu. Tall Timbers Fire Ecol. Conf., Tall Timbers Res. Stn., Tallahassee, Fla. pp. 211–219.

Appendix: Symbols

A – angle between plume and horizontal, degrees.

b – variable group comprising g, d, c, and T_o.

c – specific heat of air, kcal/kg-°K.

d – density of air, kg/m^3.

g – acceleration due to gravity, m/s^2.

h – height at temperature rise ΔT, m.

h_s – lethal scorch height, m.

I – line fire intensity, kcal/s-m.

ΔT – temperature rise above ambient, °C.

T_o – absolute ambient temperature, °K.

U – wind speed, m/s.